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Computational Fluid Dynamics Uncertainty Analysis for Payload Fairing Spacecraft Environmental Control Systems

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Problem

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- Spacecraft components may be damaged due to airflow produced by Environmental Control Systems (ECS).
- There are uncertainties and errors associated with using Computational Fluid Dynamics (CFD) to predict the flow field around a spacecraft from the ECS System.
- This paper/presentation describes an approach to estimate the uncertainty in using CFD to predict the airflow speeds around an encapsulated spacecraft without using test data.

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ECS System Overview

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- Environmental Control System

  AIAA 2002-3253

  – Prior to launch, cold air (air conditioning) flows downward around the spacecraft after it has been encapsulated in the Payload Fairing.
  – The cold air is delivered through an air-conditioning (AC) pipe, which intersects the fairing and flows past a diffuser located at the pipe/fairing interface
  – After passing over the spacecraft, it is finally discharged through vents
  – The Payload Fairing air conditioning is cut off at lift off.

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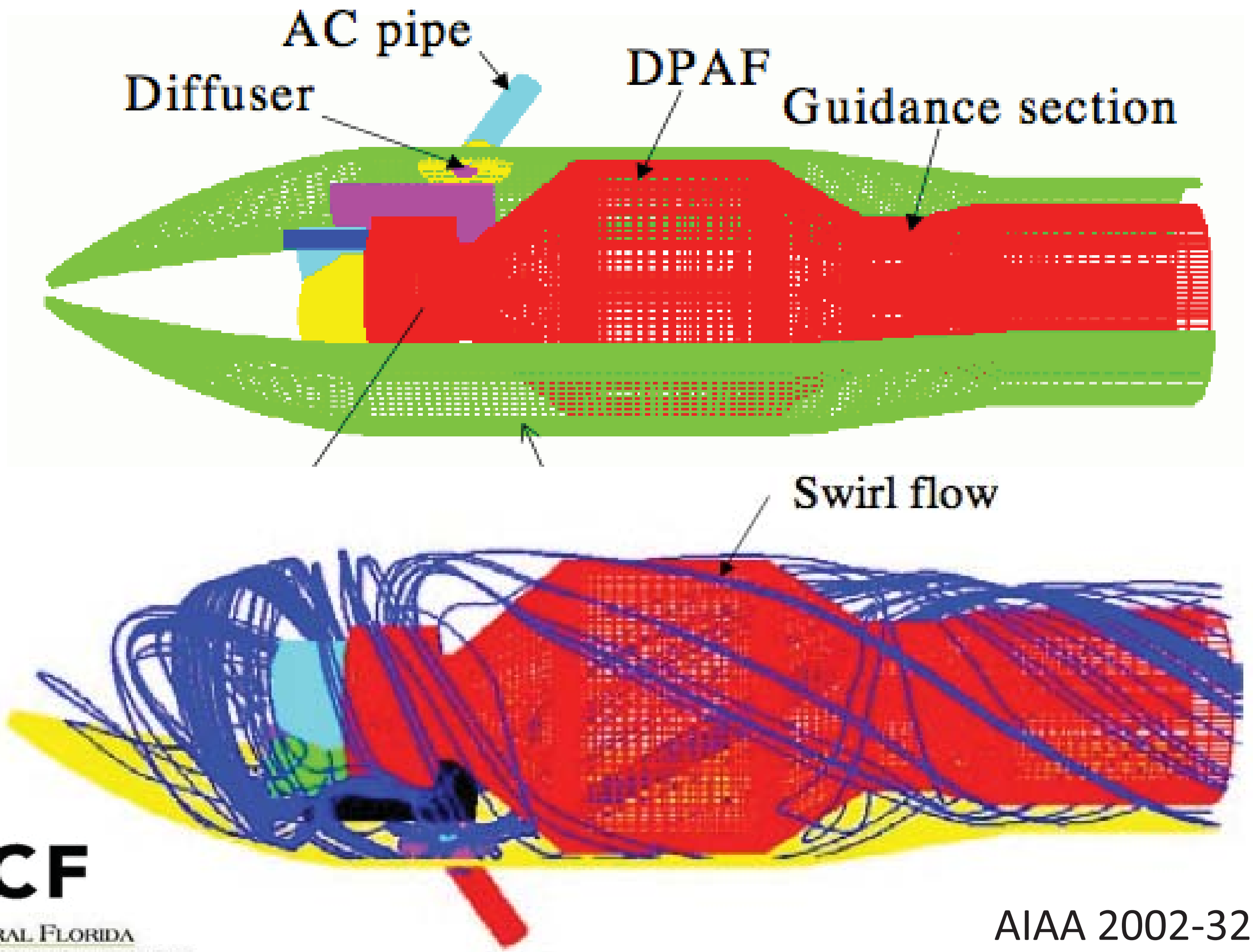
ECS System Overview

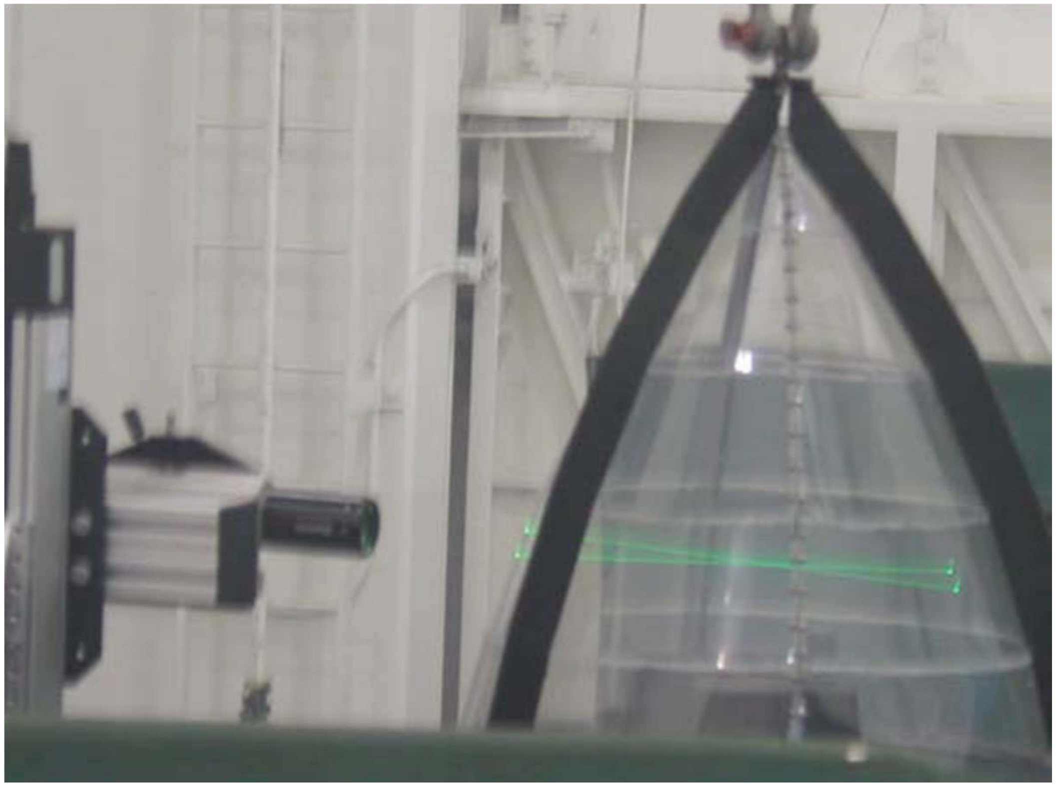
- Example of Environmental Control System (ECS) CFD Model



AIAA 2002-3253

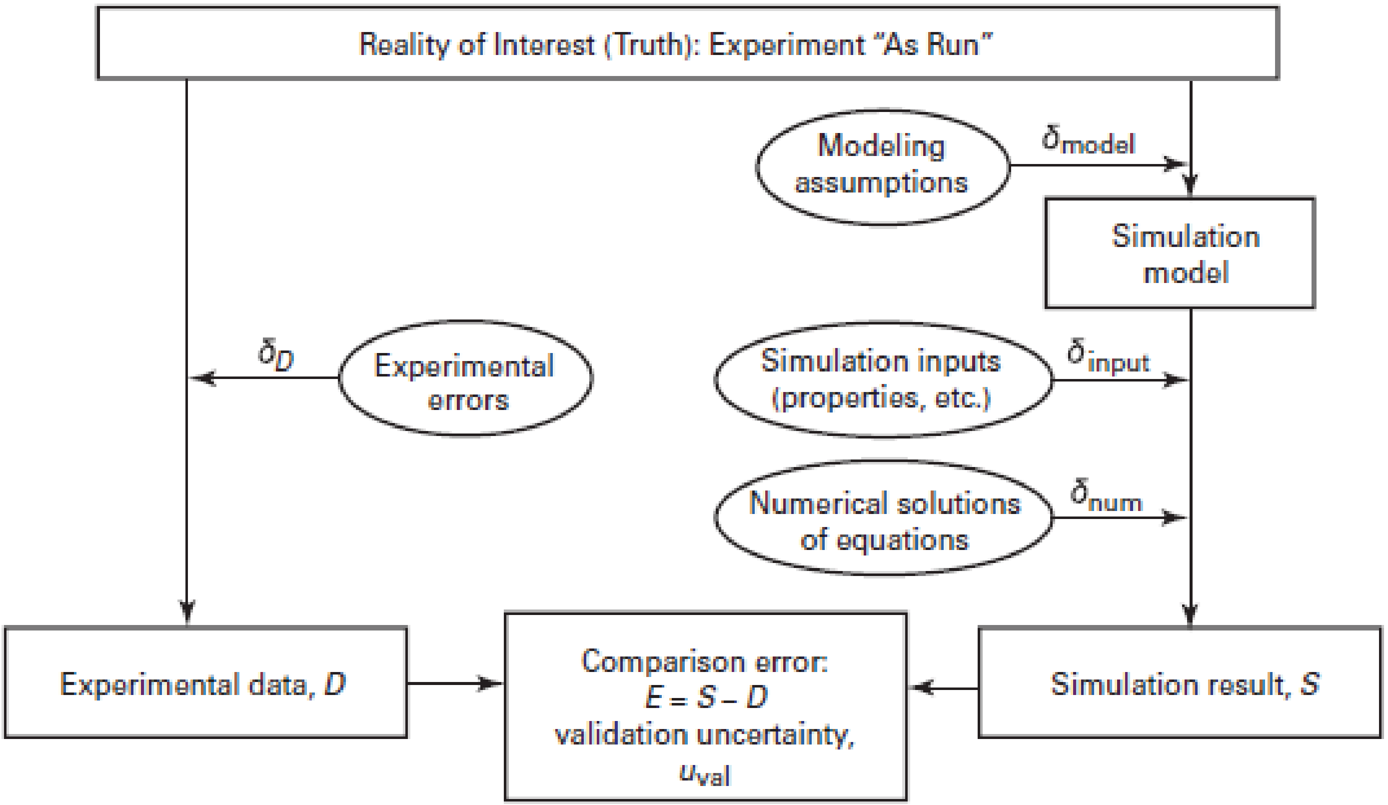
ECS System Overview

- Example of an ECS system airflow test



Kandula, M., Hammad, K., and Schallhorn, P., “CFD Validation with LDV Test Data for Payload/Fairing Internal Flow,” AIAA-2005-4910, 2005.

Overview of the Validation Process



$$E = \delta_{model} + (\delta_{input} + \delta_{num} - \delta_D)$$

ASME V&V 20-2009

Overview of the Validation Process

- Estimate Interval within which δ_{model} falls with a given degree of confidence
  - Assume Gaussian normal distribution, 90 % confidence
    - $U_{90\%} = {}_{+/-}1.65*(U_{val})$
- Error Sources (U_{num},U_{input},U_D)

$$U_{Val} = \sqrt{U_{num}^{\;2} + U_{input}^{\;2} - U_D^{\;2}}$$

- Uncertainty Equation

$$\boxed{U_{90\%} = +/-1.65 * \sqrt{U_{num}^{\;2} + U_{input}^{\;2} - U_D^{\;2}}}$$

Proposed Methodology Without Experimental Data

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Proposed Methodology **conservative estimate to envelop true value

If there is no experimental data, D=0, δ_D=0, and u_D=0.

$$E = S - D = S$$

$$\delta s = S - T$$

$$E = S - D = T + \delta s - (T + \delta_D) = \delta_S - \delta_D = \delta_S$$

$$u_{val} = k \left(\sqrt{{u_{num}}^2 + {u_{input}}^2 + {u_D}^2}\right)$$

$$u_{val} = k \left(\sqrt{{u_{num}}^2 + {u_{input}}^2}\right)$$

Report the simulated result, S as

$$S \pm u_{val}$$

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Proposed Methodology Without Experimental Data

- Report $S +/- u_s$
- *k – value (Use Student-t Distribution)*
- Treat all input variables as 'random' and run separate CFD case
- Treat as an oscillatory convergence parameter

$$U_{Oscillatory} = \frac{1}{2}(S_U - S_L)$$

Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
9	8	1.86
10	9	1.833
11	10	1.812
12	11	1.796
13	12	1.782
14	13	1.771
15	14	1.761
16	15	1.753
17	16	1.746
18	17	1.74
19	18	1.734
20	19	1.729
21	20	1.725
22	21	1.721
23	22	1.717
24	23	1.714
25	24	1.711
26	25	1.708
27	26	1.706
28	27	1.703
29	28	1.701
30	29	1.699
31	30	1.697
41	40	1.684
51	50	1.676
61	60	1.671
81	80	1.664
101	100	1.66
121	120	1.658
infty	infty	1.645

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EELV Public Available Information

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- The Rockets Behind the Missions:
  - Delta II
  - Delta IV
  - Atlas V
  - Pegasus
  - Taurus
  - Falcon 9

- http://www.nasa.gov/centers/kennedy/launchingrockets/

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EELV Public Available Information

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- Each of these vehicles have a Payload Planners Guide or Users Guide
- http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIIPayloadPlannersGuide2007.pdf
- http://spacecraft.ssl.umd.edu/design_lib/Delta4.pl.guide.pdf
- http://spacecraft.ssl.umd.edu/design_lib/Atlas5.pl.guide.pdf
- http://www.orbital.com/NewsInfo/Publications/Pegasus_UG.pdf
- http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf
- http://www.spacex.com/Falcon9UsersGuide_2009.pdf

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Delta II

- Air-conditioning is supplied to the spacecraft via an umbilical after the payload fairing is mated to the launch vehicle.
- The payload air-distribution system provides air at the required temperature, relative humidity, and flow rate as measured
- The air-distribution system uses a diffuser on the inlet air-conditioning duct at the fairing interface.
- If required, a deflector can be installed on the inlet to direct the airflow away from sensitive spacecraft components
- The air can be supplied to the payload between a rate of
- 1300 to 1700 scfm.
- Diameter of Fairing is 3meters

http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIIPayloadPlannersGuide2007.pdf

Delta II - Continued

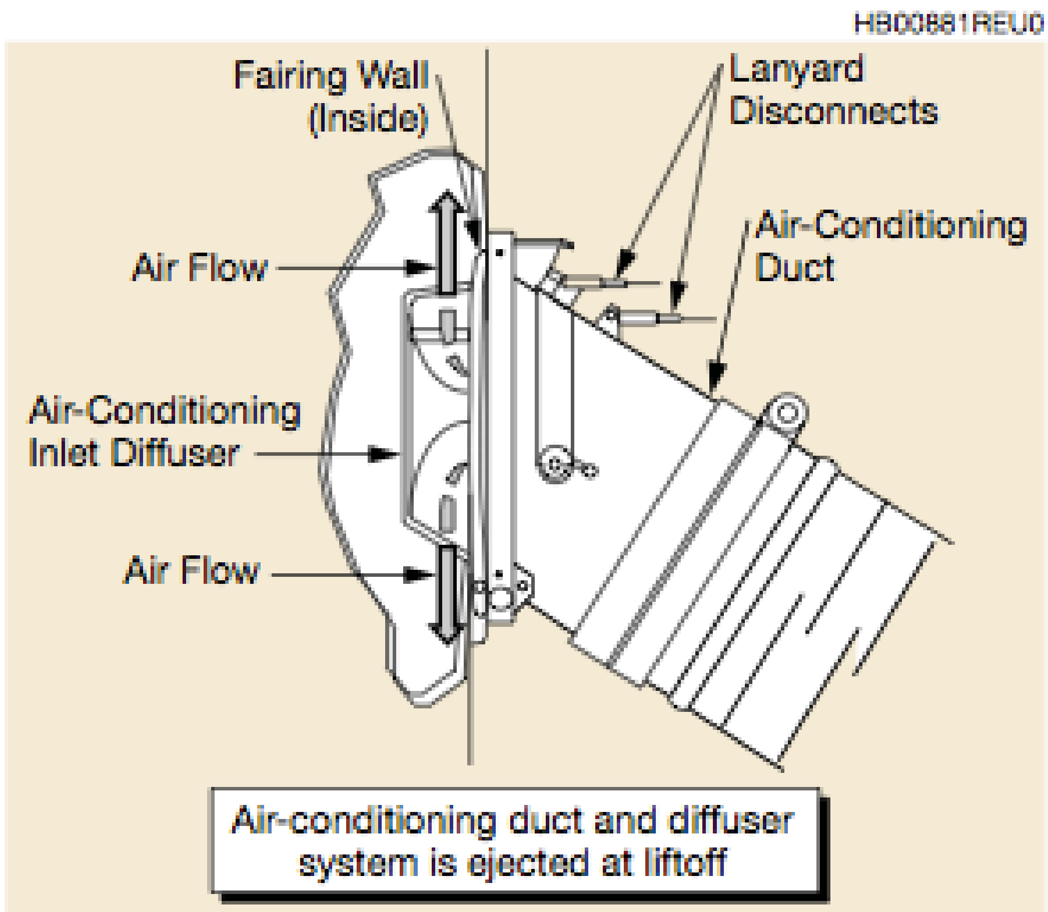


Figure 4-1. Payload Air Distribution System

http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIIPayloadPlannersGuide2007.pdf

Delta IV

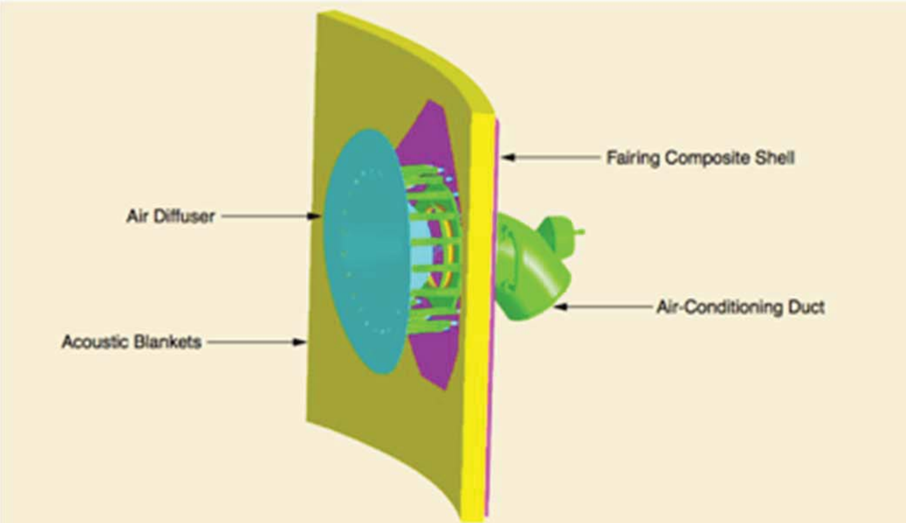


Figure 4-1. Standard 4-m Composite Fairing and 5-m Composite Fairing Air-Conditioning Duct Inlet Configuration

The air is supplied to the payload at a maximum flow rate of 36.3 kg/min to 72.6 kg/min (80 to 160 lb/min) for 4-m fairing launch vehicles and 90.7 kg/min to 136.0 kg/min (200 to 300 lb/min) for 5-m fairing launch vehicles.

Air flows around the payload and is discharged through vents in the aft end of the fairing.

Fairing sizes 4meter and 5 meters in diameter

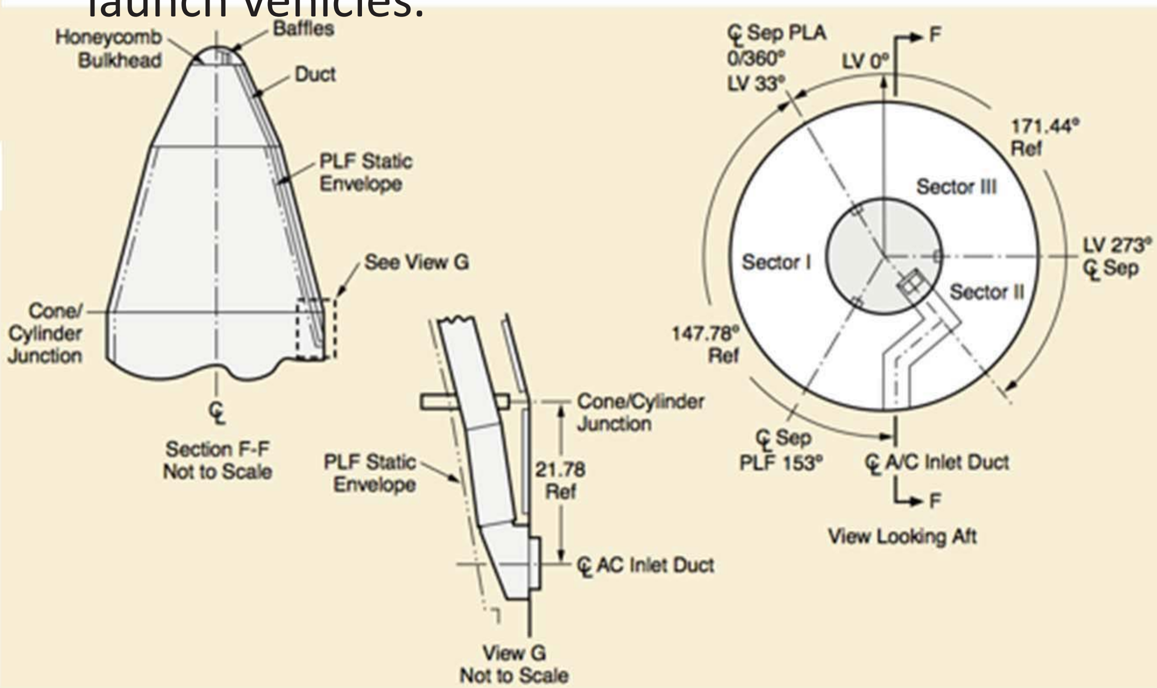


Figure 4-2. 5-m Metallic Fairing Payload Air-Distribution System

http://spacecraft.ssl.umd.edu/design_lib/Delta4.pl.guide.pdf

Atlas V

- Internal ducting defectors in the PLF direct the gas upward to prevent direct impingement on the spacecraft.
- The conditioning gas is vented to the atmosphere through one-way flapper doors below the spacecraft.
- The PLF air distribution system will provide a maximum air flow velocity in all directions of no more than 9.75 mps (32 fps) for the Atlas V 400 and 10.67 mps (35 fps) for the Atlas V 500.
- There will be localized areas of higher flow velocity at, near, or associated with the air conditioning outlet.
- Maximum air flow velocities correspond to maximum inlet mass flow rates.
- Reduced flow velocities are achievable using lower inlet mass flow rates.

- Flow Rates
  A) Atlas V 400: 0.38–1.21 kg/s ±0.038 kg/s (50–l60 lb/min ±5 lb/min),
  B) Atlas V 500: 0.38–2.27 kg/s ±0.095 kg/s (50–300 lb/min ±12.5 lb/min)

- Fairing sizes are 4meters and 5 meters in diameter

http://spacecraft.ssl.umd.edu/design_lib/Atlas5.pl.guide.pdf

Pegasus

- The fairing is continuously purged with filtered air.
- The flowrate of air through the fairing is maintained between 50 and 200 cfm.
- The air flow enters the fairing forward of the payload and exits aft of the payload. There are baffles on the inlet that minimize the impingement velocity of the air on the payload.
- Fairing diameter is 0.97 meters

http://www.orbital.com/NewsInfo/Publications/Pegasus_UG.pdf

Taurus

- Upon encapsulation within the fairing and for the remainder of ground operations, the payload environment will be maintained by the Taurus Environmental Control System (ECS).
- Fairing inlet conditions are selected by the Customer
- Fairing diameters are 63 inches and 92 inches

http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf

Falcon 9

- Once fully encapsulated and horizontal, the Environmental Control System (ECS) is connected
- Payload environments during various processing phases are:
  - In hanger, encapsulated – Flow Rate: 1,000 cfm
  - During rollout: 1,000 cfm
  - On pad: Variable from 1000 to 4500 cfm
- Fairing diameter is 5.2 meters

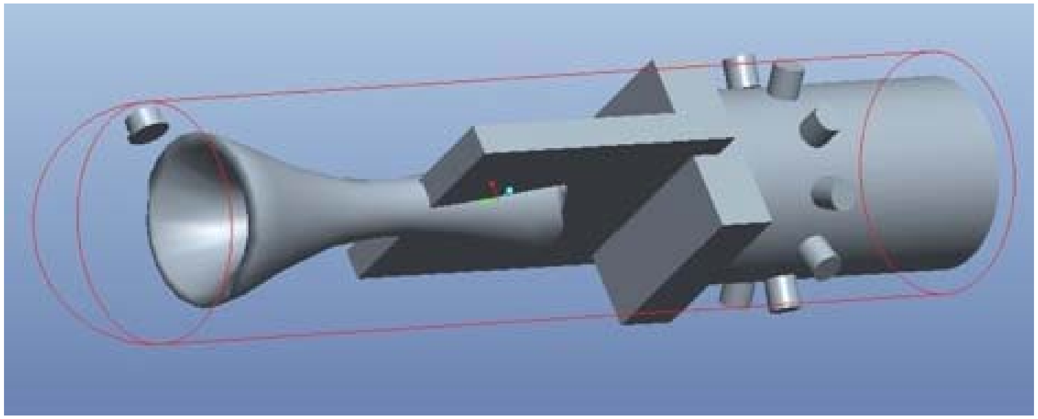
http://www.spacex.com/Falcon9UsersGuide_2009.pdf

(3) Configurations

- Fairing Sizes are approximately 1m, 1.6m, 2.3m, 3m, 4m, 5m in diameter.
- (3) generic fairing diameters are selected to envelop the EELV fairing configurations
  - 0.75m
  - 3.5 m
  - 5.5 m
- Inlet Conditions range from 1000 cfm to 4500 cfm
- Spacecraft diameters range with fairing sizes, a generic spacecraft was drawn and scaled accordingly

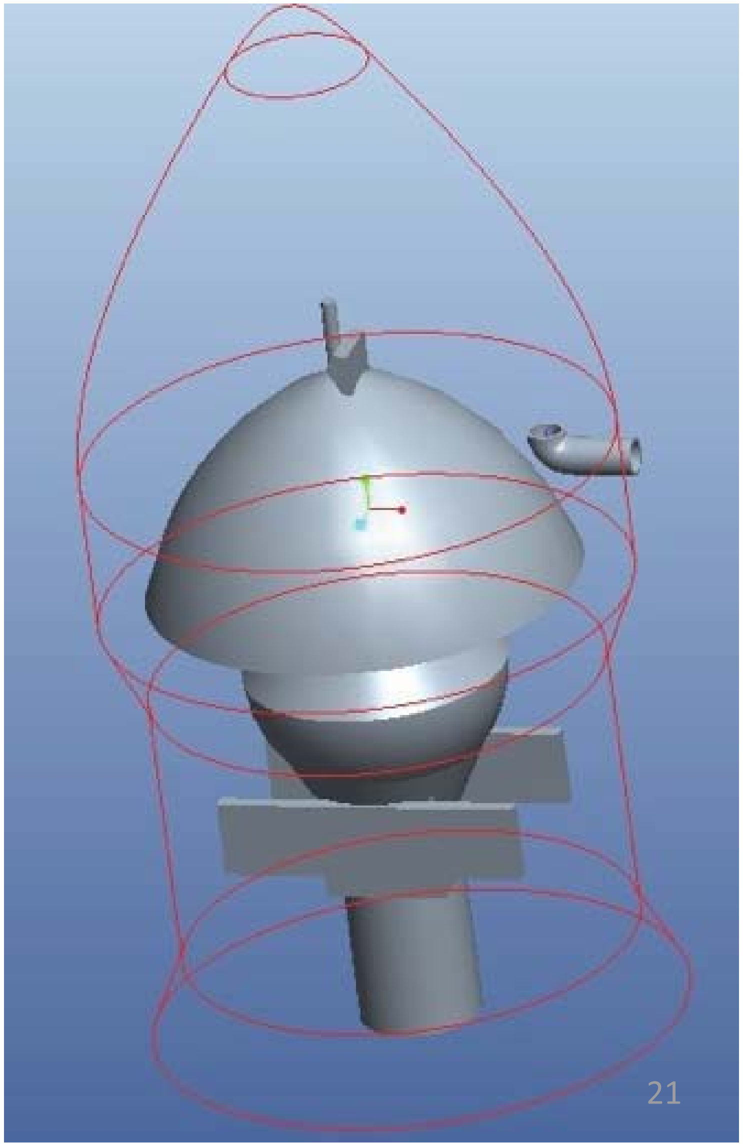
(3) Configurations

- CAD model of the spacecraft was created in Pro/ENGINEER, 0.75m



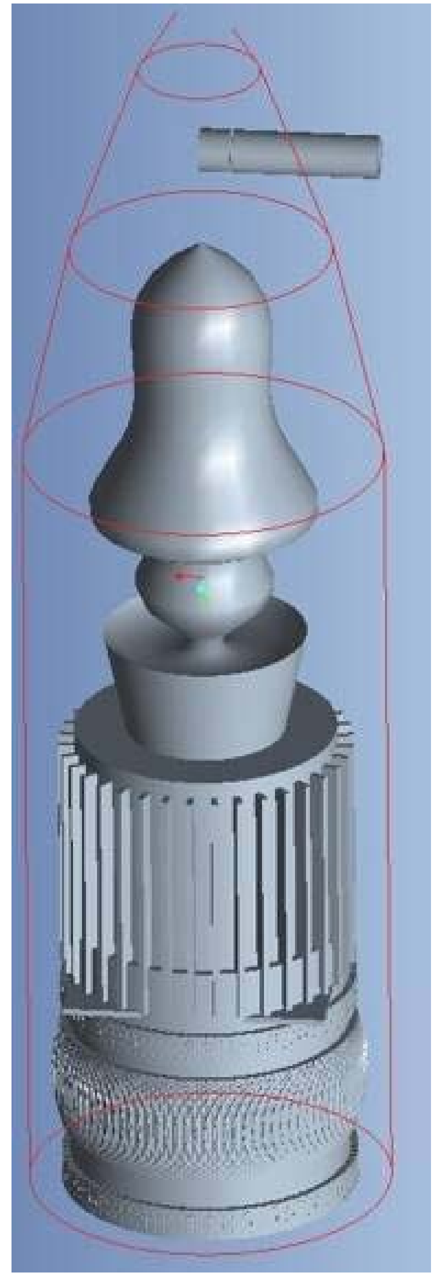
(3) Configurations

- 3.5m



(3) Configurations

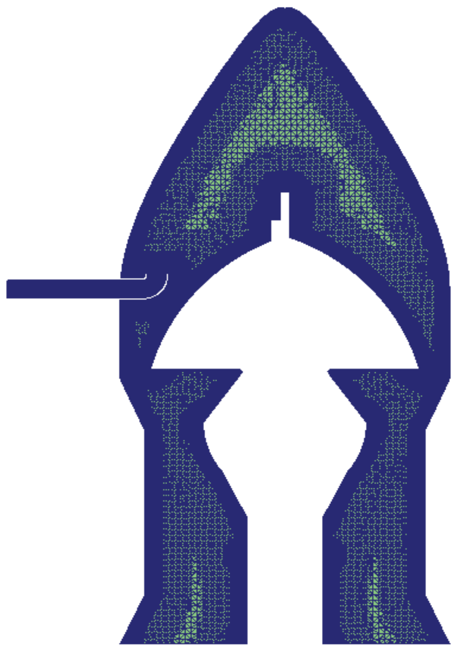
- 5.5m



CFD Modeling

- Snappy Hex – Mesher

0.75m Configuration (6762865 number of cells)



3.5m Configuration (8594480 number of cells)

5.5m Configuration (6980673number of cells)

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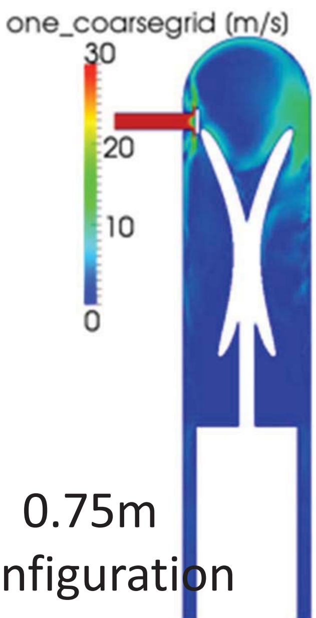
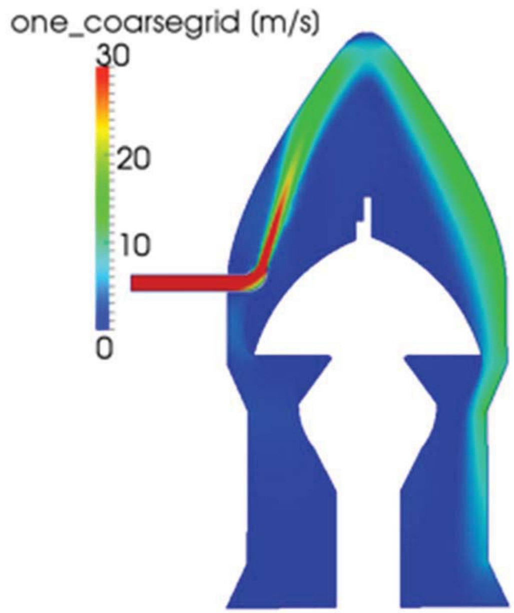
CFD Modeling

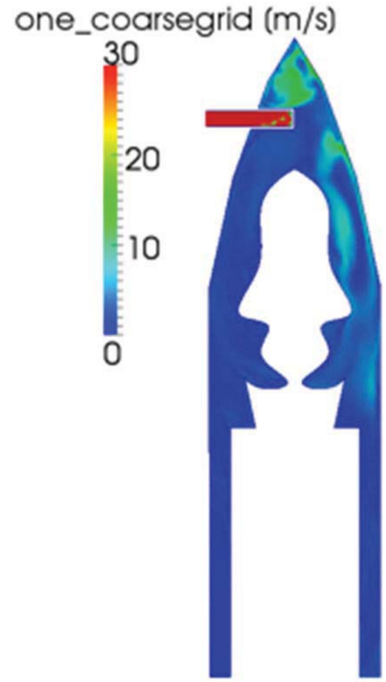
- OpenFoam - SimpleFoam



0.75m Configuration (6762865 number of cells)



3.5m Configuration (8594480 number of cells)



5.5m Configuration (6980673number of cells)

Uncertainty Calculation

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- Proposed Methodology

$$S \, {}^{+}_{-} u_{val}$$

$$u_{val} = k\left(\sqrt{{u_{num}}^{2} + {u_{input}}^{2}}\right)$$

- Expanding

Input Variable	Description	Bias
Grid	3 grids considered for each configuration	
Inlet Velocity	Boundary Condition low and high	10%
Outlet Pressure	Boundary Condition low and high	2%
Turbulence Model	SA, ke-realizable, kwSST	
Wall Functions	with and without	
Rough Wall Function	smooth vs. rough	
Compressibility	incompressible vs. compressible	
Solver	OpenFoam, Fluent, STARCCM+	
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05

$$u_{val} = k\left(\left(\left(\frac{\partial V}{\partial grid}\right)^{2} B_{grid}^{2}\right) + \left(\left(\frac{\partial V}{\partial pressure}\right)^{2} B_{pressure}^{2}\right) + \left(\left(\frac{\partial V}{\partial velocity}\right)^{2} B_{velocity}^{2}\right) + \left(\left(\frac{\partial V}{\partial rho}\right)^{2} B_{rho}^{2}\right) + \left(\left(\frac{\partial V}{\partial wall\ functions}\right)^{2} B_{wall\ functions}^{2}\right) + \left(\left(\frac{\partial V}{\partial surface\ roughness}\right)^{2} B_{surface\ roughness}^{2}\right) + \left(\left(\frac{\partial V}{\partial compressibility}\right)^{2} B_{compressibility}^{2}\right) + \left(\left(\frac{\partial V}{\partial solver}\right)^{2} B_{solver}^{2}\right) + \left(\left(\frac{\partial V}{\partial turbulence}\right)^{2} B_{turbulence}^{2}\right)\right)^{1/2}$$

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Uncertainty Calculation

Case #	Parameter		Configuration 0.75	3.5	5.5
	Grid				
1		coarse	1	1	1
2		med	2	2	2
3		fine	3	3	3
	Boundary Conditions				
4		inlet velocity low	4	4	4
5		inlet velocity high	5	5	5
6		pressure outlet low	6	6	6
7		pressure outlet high	7	7	7
	Turbulence Models				
8		SA	8	8	8
9		ke-realizable - same as1	9	9	9
10		kwsst	10	10	10
11	Wall Functions	without wall functions	11	11	11
12	Surface Roughness	rough wall function	12	12	12
13	Compressibility	different openfoam solver	13	13	13
	Solver				
14		fluent	14	14	14
15		starccm	15	15	15
	Fluid Properties				
16		nut high	16	16	16
17		nut low	17	17	17

$$u_{val} = 1.746 * \left|\frac{1}{2}(S_U - S_L)\right|$$

Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
9	8	1.86
10	9	1.833
11	10	1.812
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13	12	1.782
14	13	1.771
15	14	1.761
16	15	1.753
17	16	1.746
18	17	1.74
19	18	1.734
20	19	1.729
21	20	1.725
22	21	1.721
23	22	1.717
24	23	1.714
25	24	1.711
26	25	1.708
27	26	1.706
28	27	1.703
29	28	1.701
30	29	1.699
31	30	1.697
41	40	1.684
51	50	1.676
61	60	1.671
81	80	1.664
101	100	1.66
121	120	1.658
infty	infty	1.645

Results 0.75m Configuration

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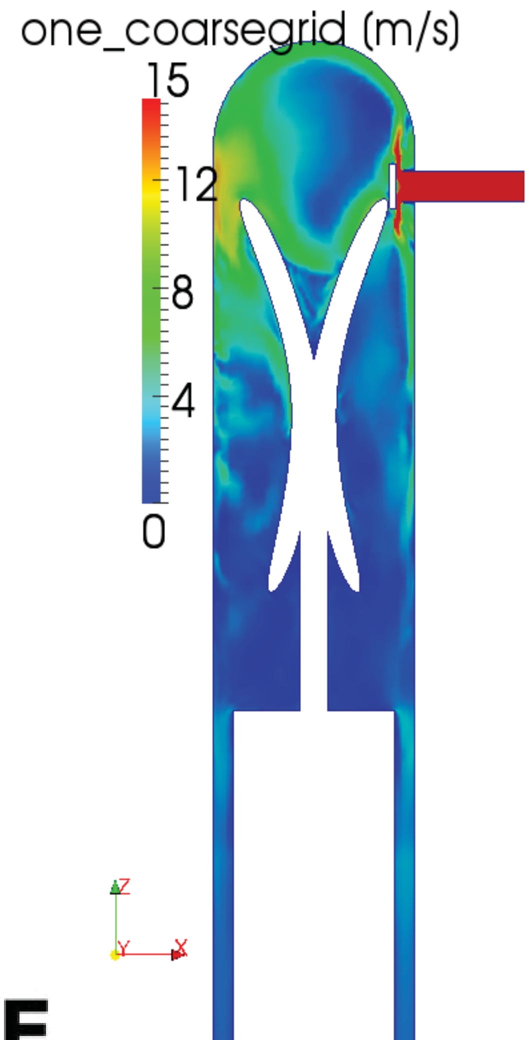
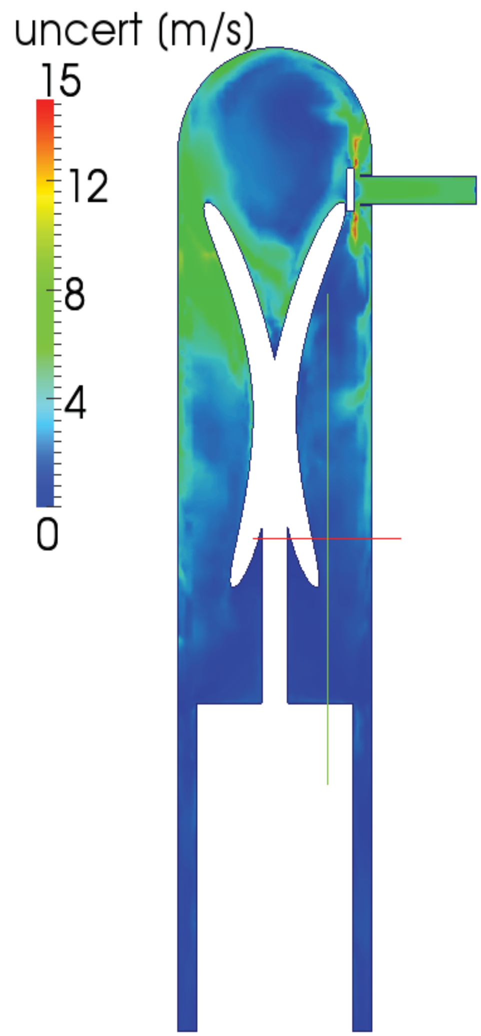
- Solution and Uncertainty Contour Plots





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Results 0.75m Configuration

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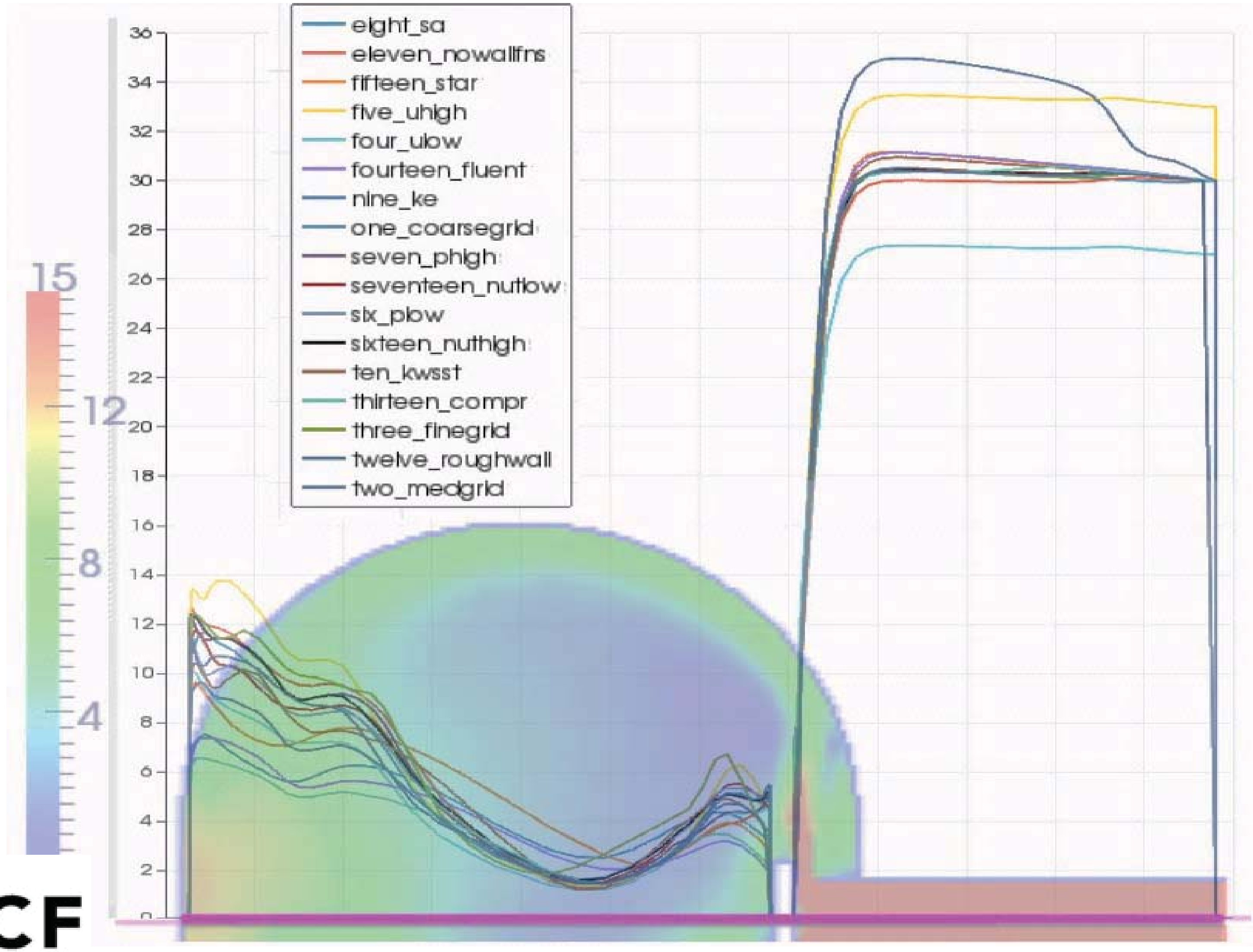
- Solution Line Plot



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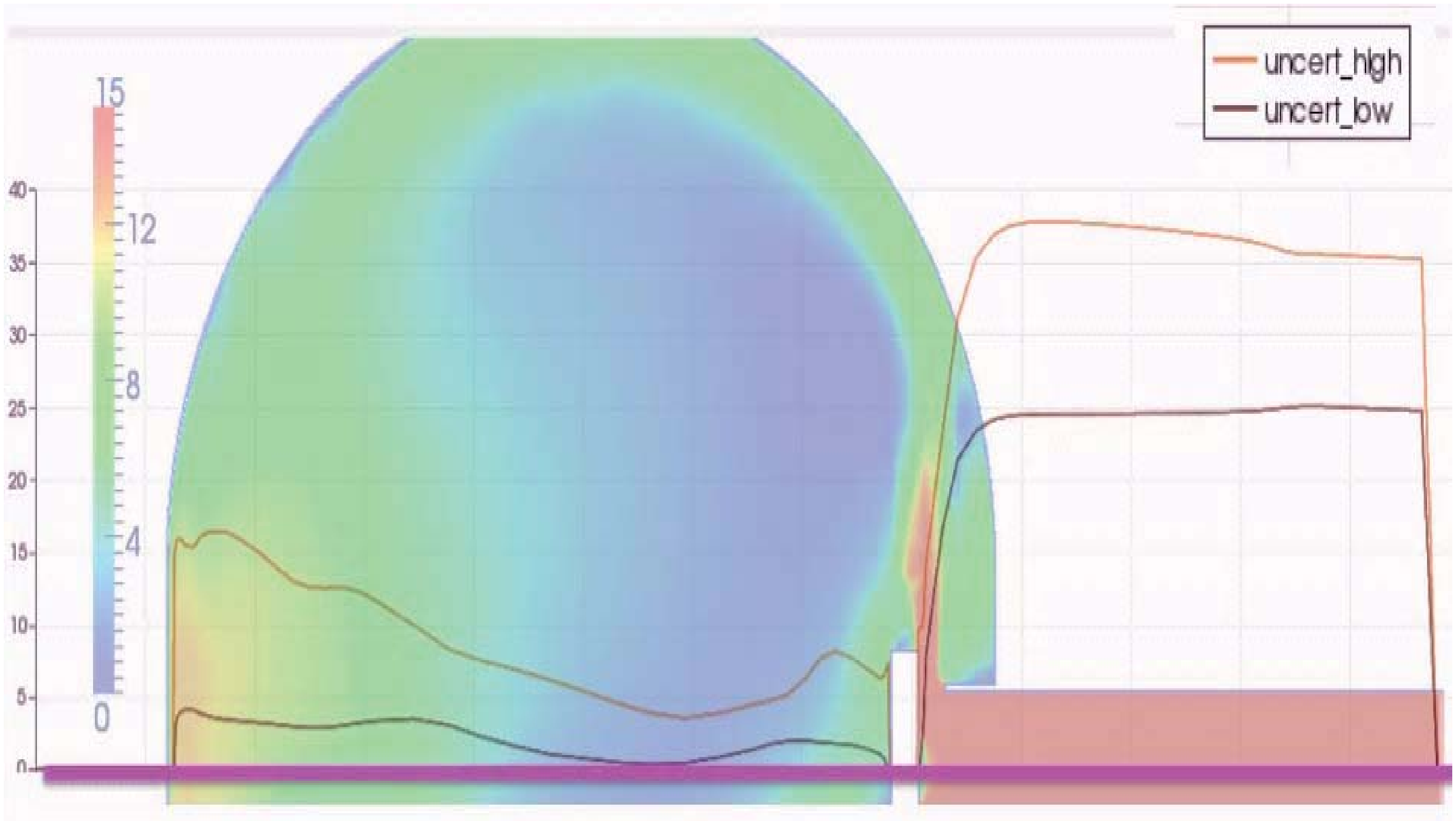
Results 0.75m Configuration

- Uncertainty Line Plot



Results 0.75m Configuration

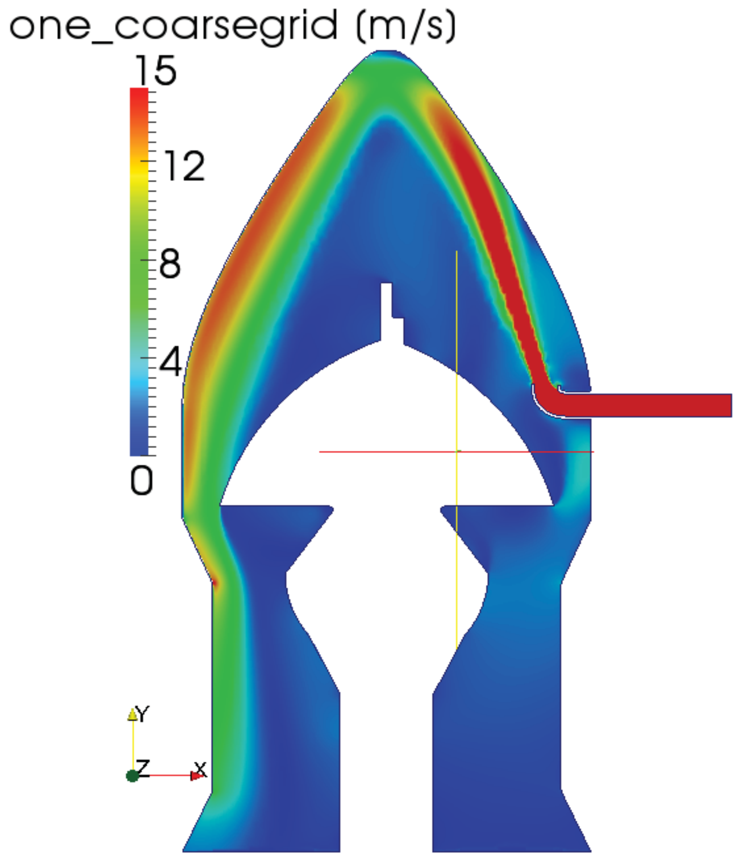
- ## Uncertainty Ranking

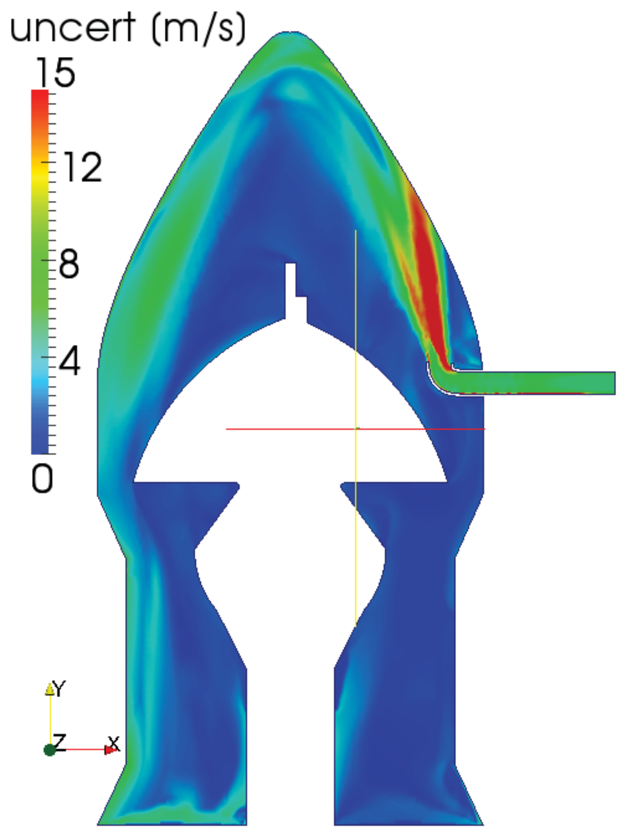
- The uncertainty for each of the input variables were ranked by the non-dimensionalizing the difference in the results by the freestream value and ranking from greatest uncertainty to least uncertainty.

Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		1.6287	0.0543	13.40	2
Inlet Velocity	Boundary Condition	10%	1.3115	0.04737	11.69	5
Outlet Pressure	Boundary Condition	2%	1.1478	0.0383	9.45	8
Turbulence Model	SA, ke-realizable, kwSST		1.4628	0.0488	12.04	4
Wall Functions	with and without		0.8286	0.0276	6.81	9
Rough Wall Function	smooth vs. rough		1.5237	0.0508	12.53	3
Compressibility	incompressible vs. compressible		1.3128	0.0438	10.81	6
Solver	OpenFoam, Fluent, STARCCM+		1.673	0.0558	13.77	1
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	1.1536	0.0385	9.50	7

Results 3.5m Configuration

- Solution and Uncertainty Contour Plots





Results 3.5m Configuration

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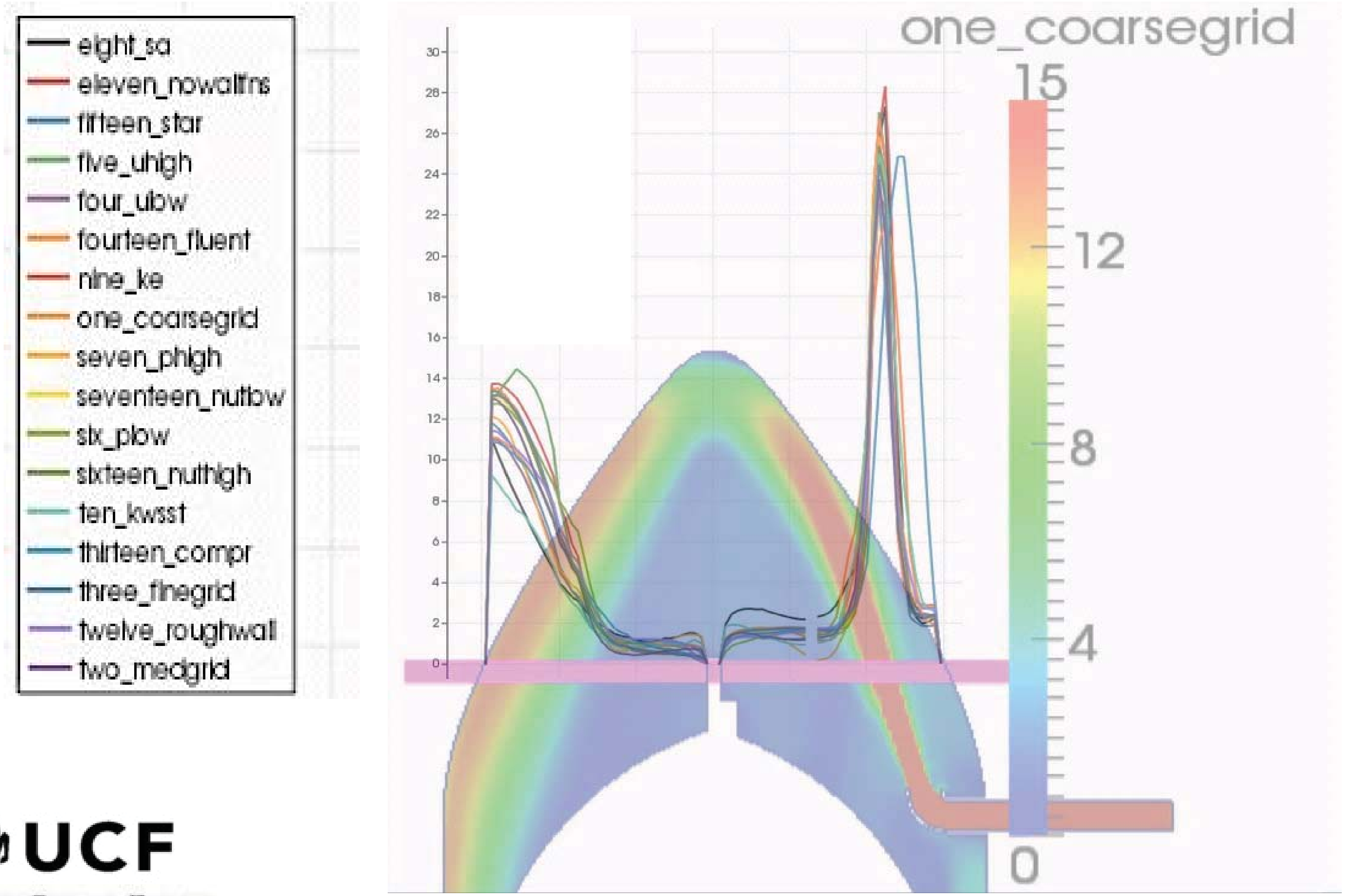
- Solution Line Plot



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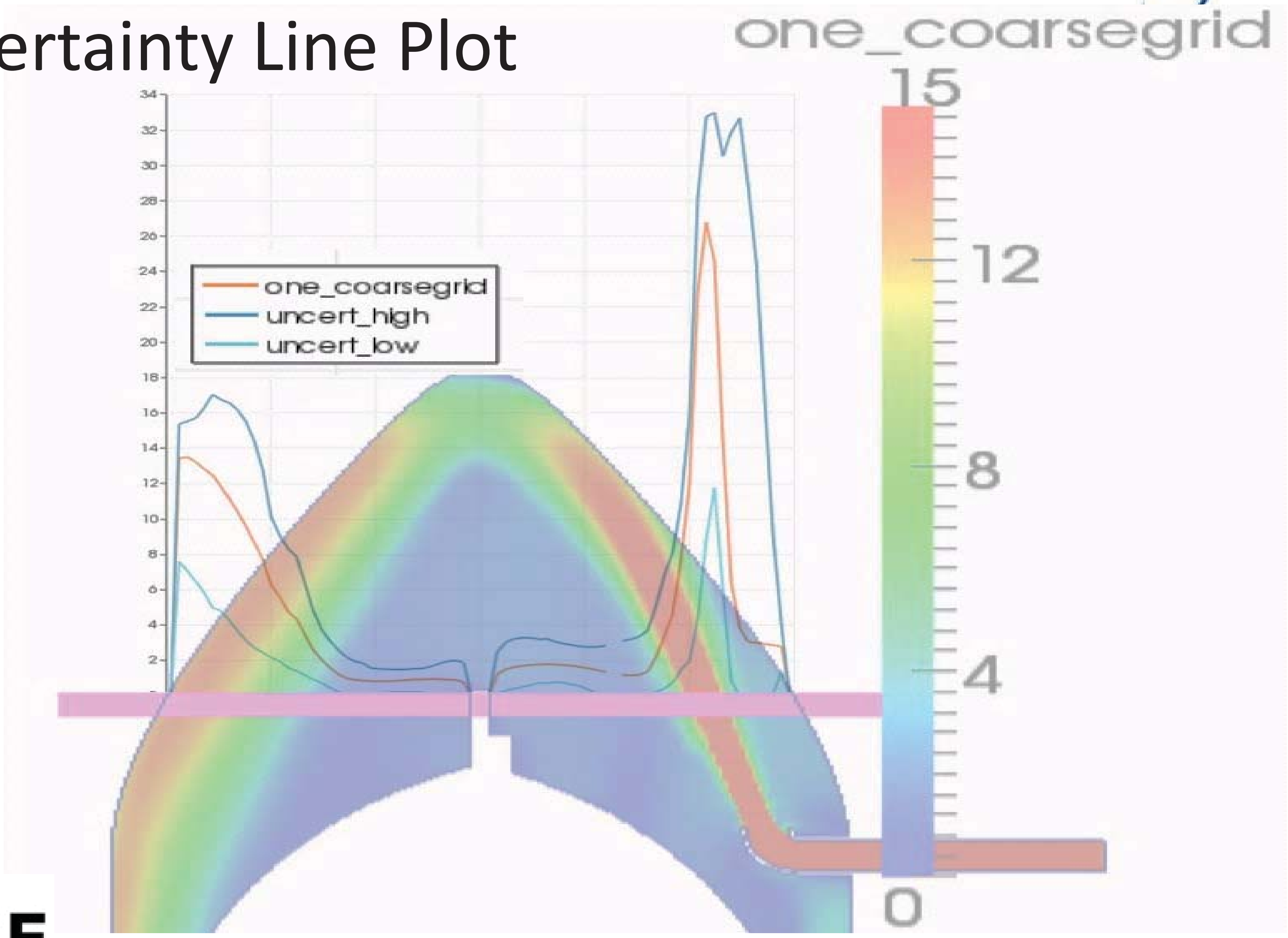
Results 3.5m Configuration

- Uncertainty Line Plot



Results 3.5m Configuration

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- Uncertainty Ranking

Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		0.6829	0.0228	8.28	7
Inlet Velocity	Boundary Condition	10%	0.7919	0.0264	9.59	6
Outlet Pressure	Boundary Condition	2%	1.4606	0.0487	17.70	1
Turbulence Model	SA, ke-realizable, kwSST		1.3487	0.045	16.35	2
Wall Functions	with and without		0.6139	0.0205	7.45	9
Rough Wall Function	smooth vs. rough		1.0531	0.0351	12.75	3
Compressibility	incompressible vs. compressible		0.8252	0.0275	9.99	5
Solver	OpenFoam, Fluent, STARCCM+		0.841	0.028	10.17	4
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	0.6345	0.0212	7.70	8

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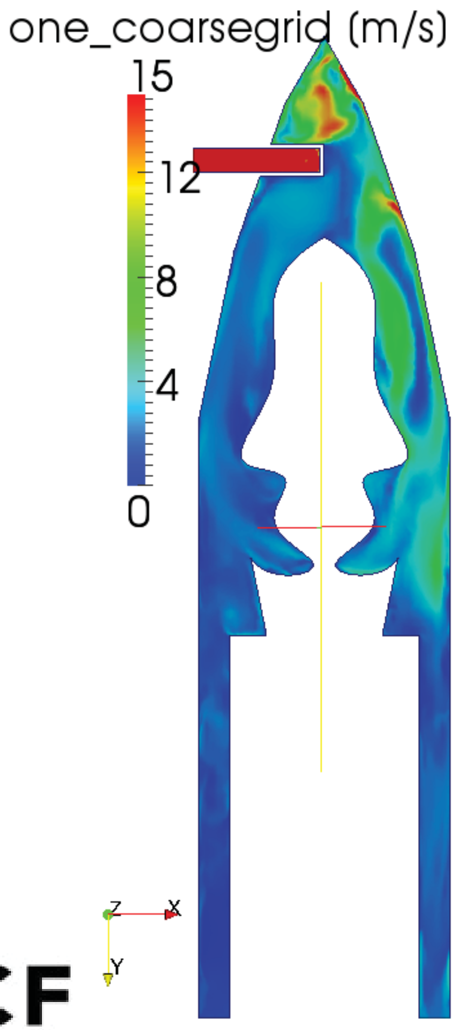
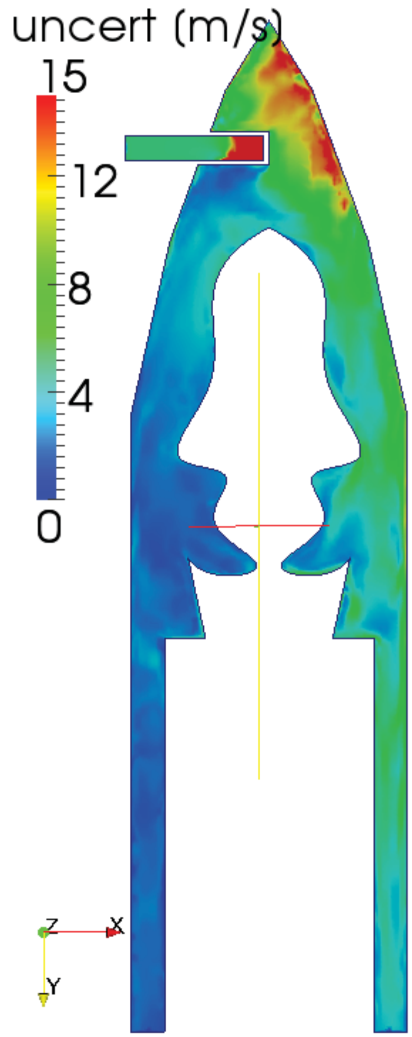
Results 5.5m Configuration

- Solution and Uncertainty Contour Plots





Results 5.5m Configuration

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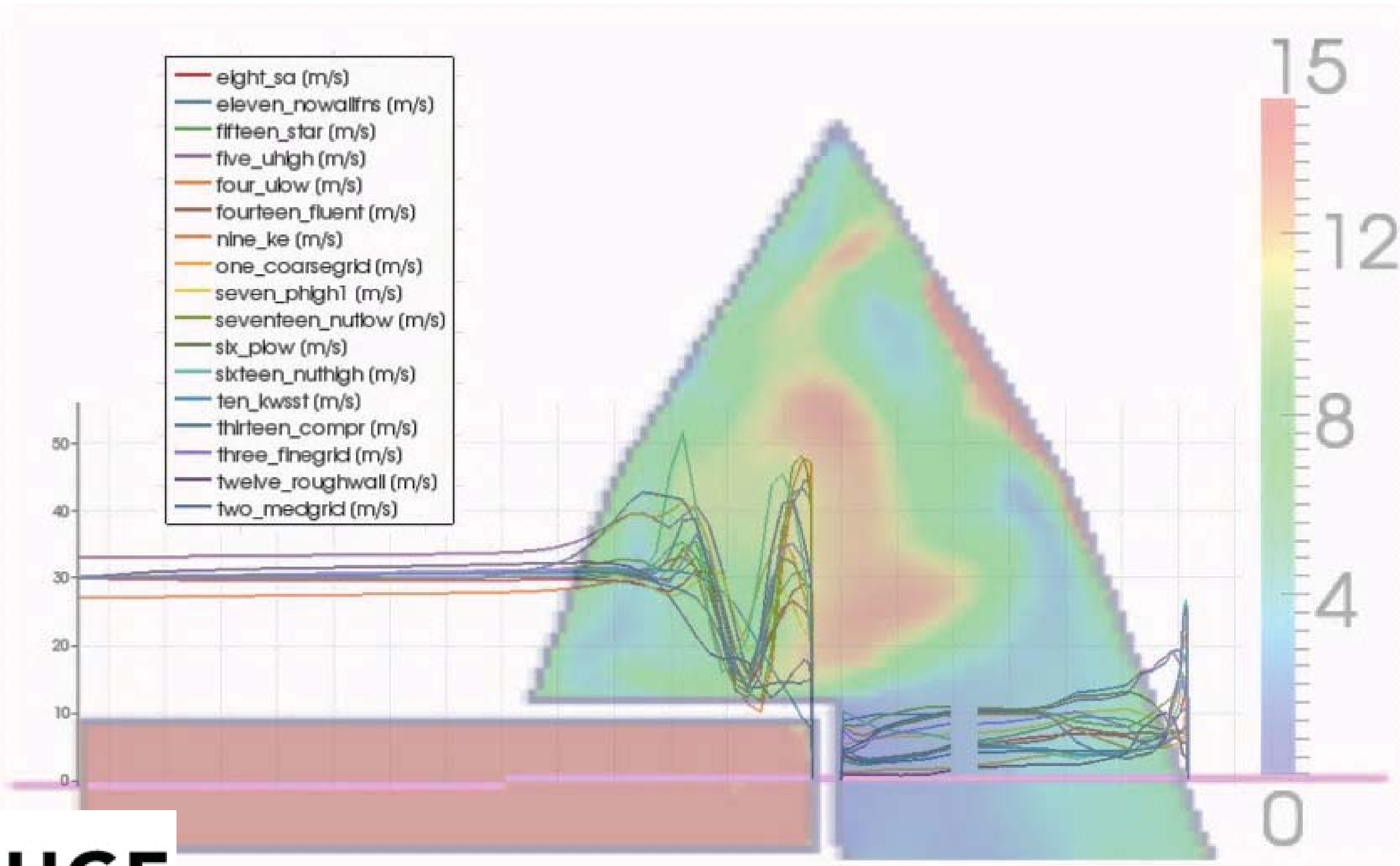
- Solution Line Plot



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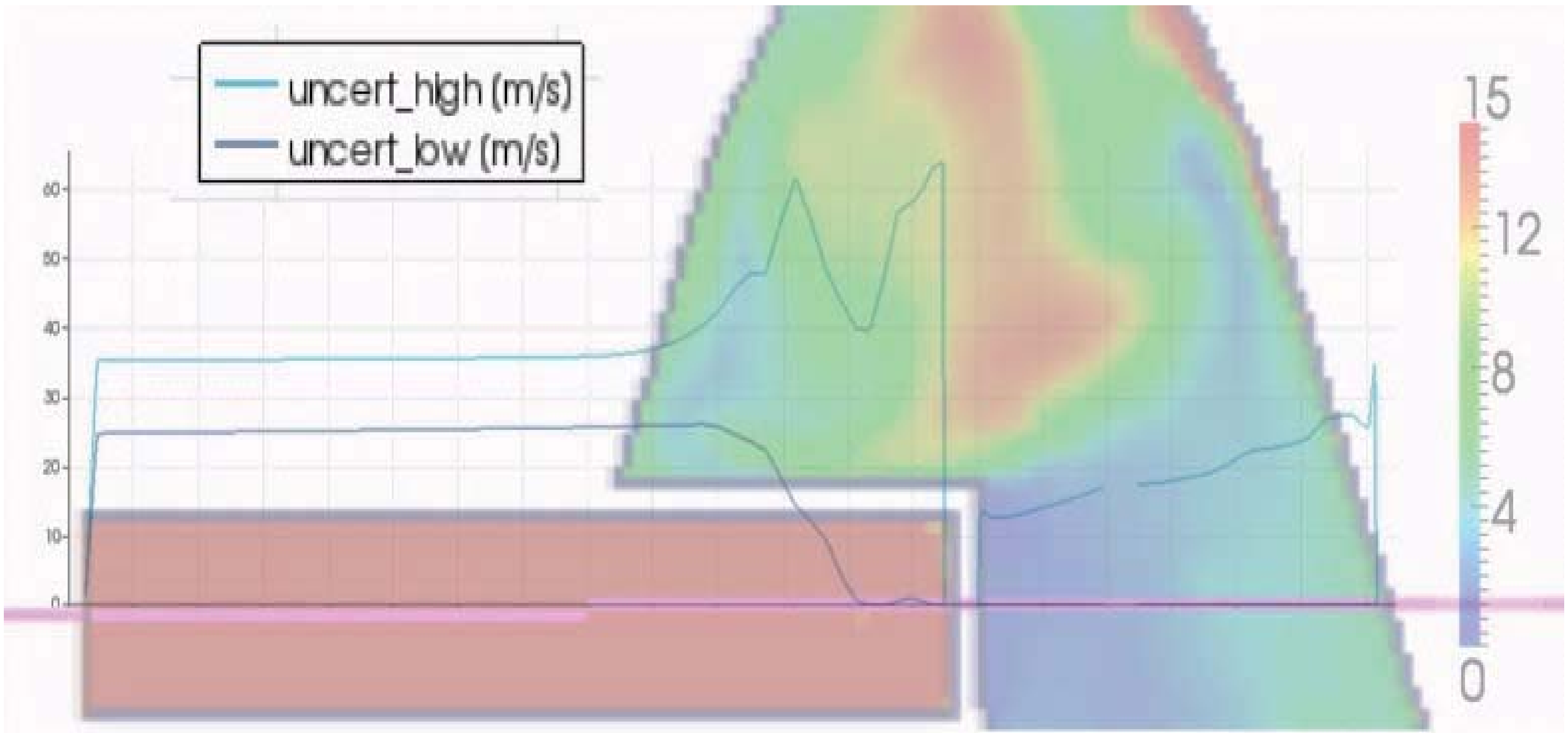
Results 5.5m Configuration

- Uncertainty Line Plot



Results 3.5m Configuration

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LAUNCH SERVICES PROGRAM

- Uncertainty Ranking

Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		2.0203	0.0673	12.44	3
Inlet Velocity	Boundary Condition	10%	1.6198	0.054	9.98	6
Outlet Pressure	Boundary Condition	2%	2.0173	0.0672	12.42	4
Turbulence Model	SA, ke-realizable, kwSST		2.3049	0.0768	14.19	1
Wall Functions	with and without		1.4902	0.0497	9.18	7
Rough Wall Function	smooth vs. rough		1.4901	0.0497	9.18	8
Compressibility	incompressible vs. compressible		1.4256	0.0475	8.78	9
Solver	OpenFoam, Fluent, STARCCM+		1.8172	0.0606	11.20	5
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	2.05	0.0683	12.62	2

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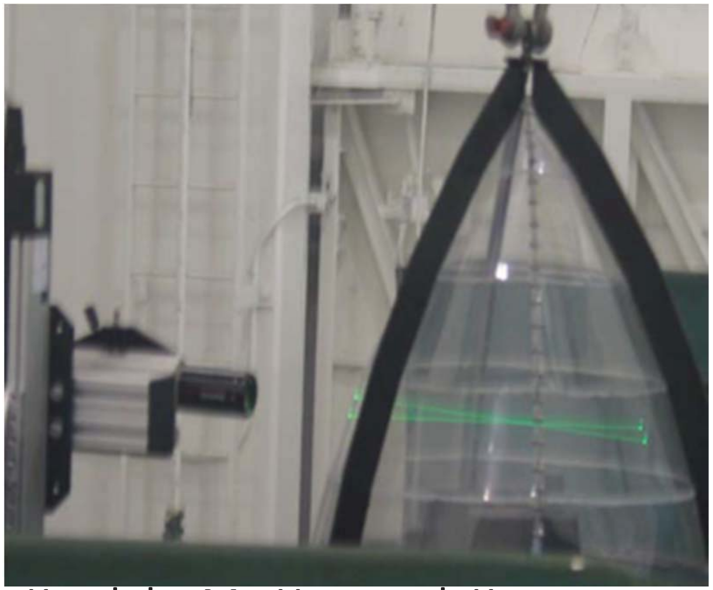
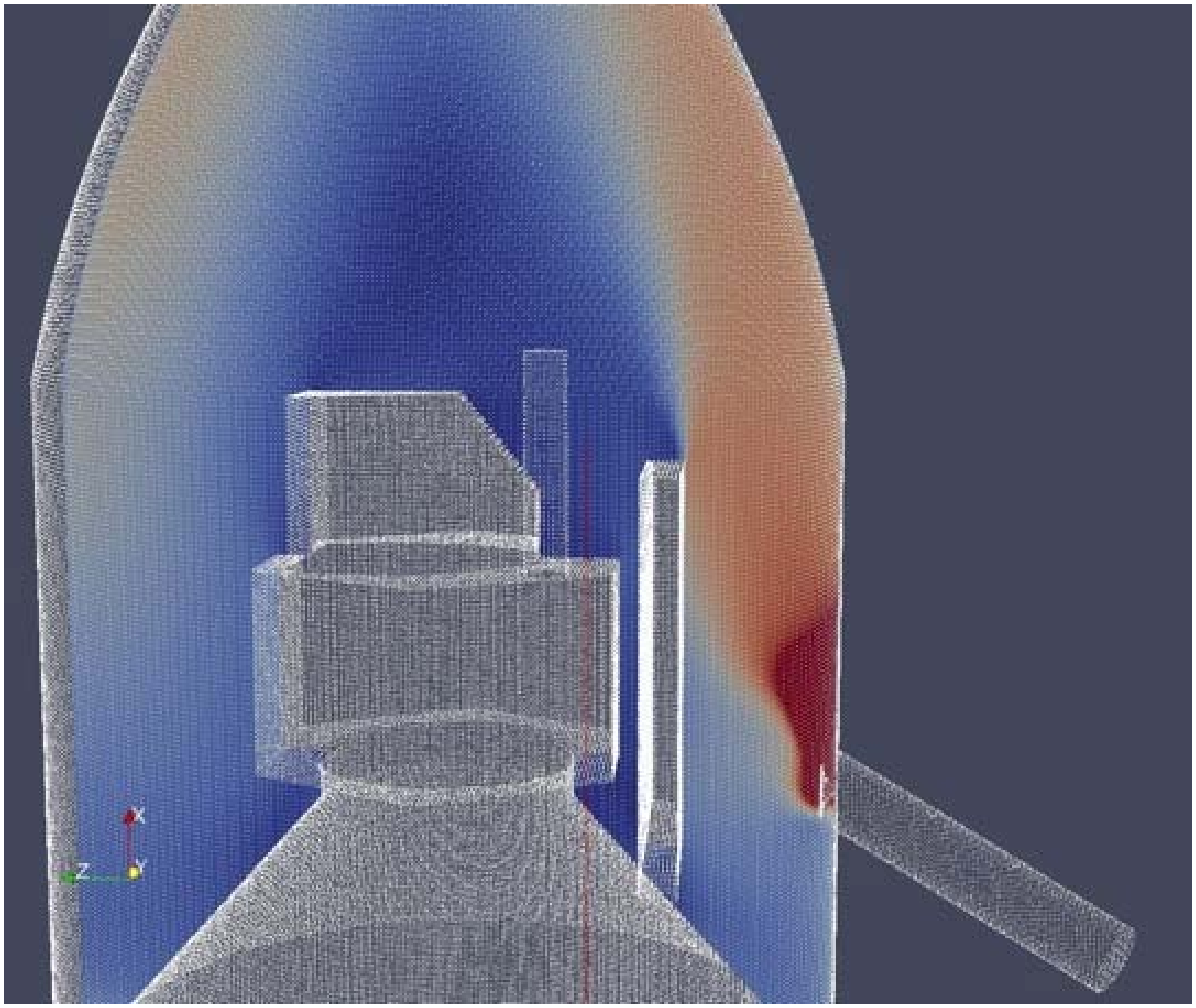
Comparison to Previous LDV Test

Variable	Bias
Velocity Inlet	3%
Kinematic Viscosity [0-100] Deg C	[1.36, 1.50, 2.306] e-5 m2/s
Pressure Outlet	3%
Turbulence	ke-realiazable, kwsst, SA



Kandula, M., Hammad, K., and Schallhorn, P., "CFD Validation with LDV Test Data for Payload/Fairing Internal Flow," AIAA-2005-4910, 2005.



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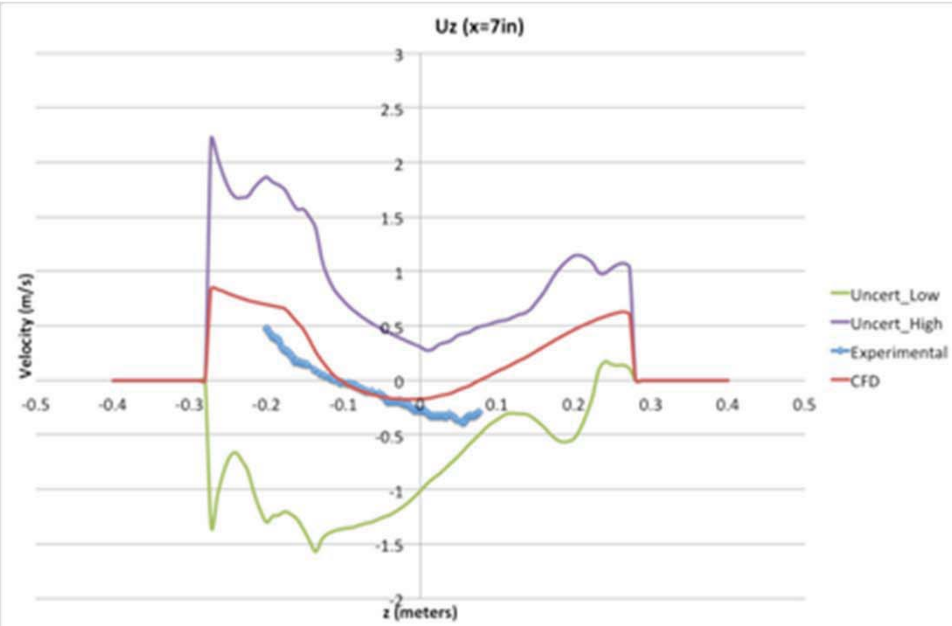
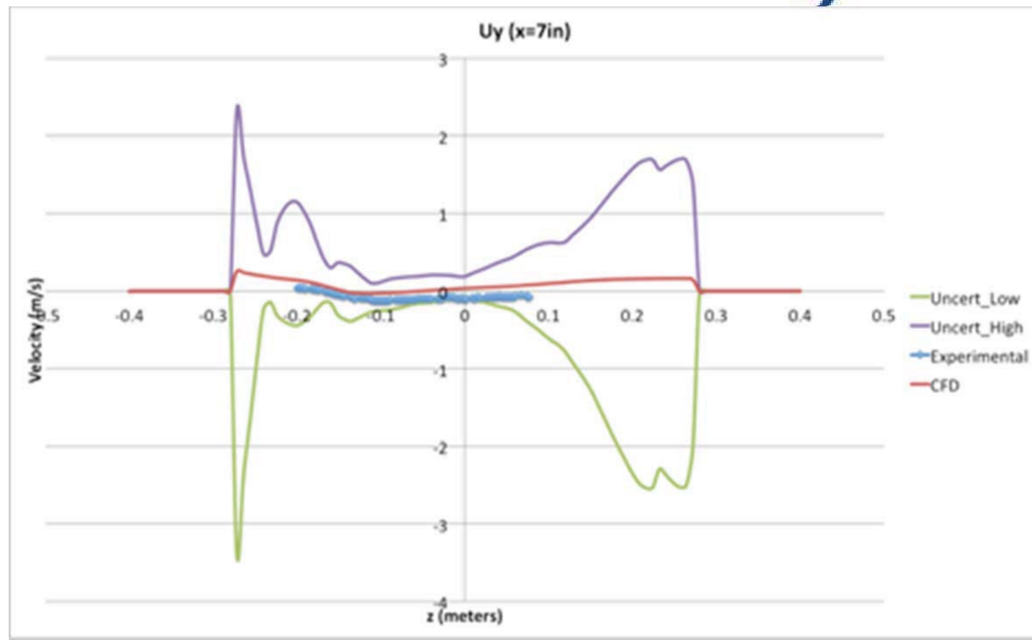
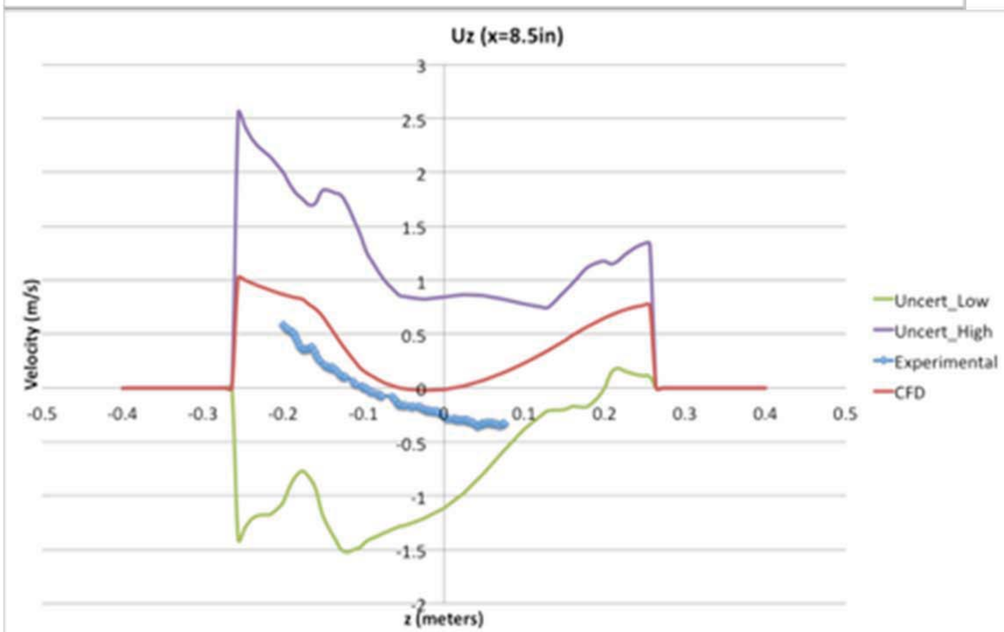
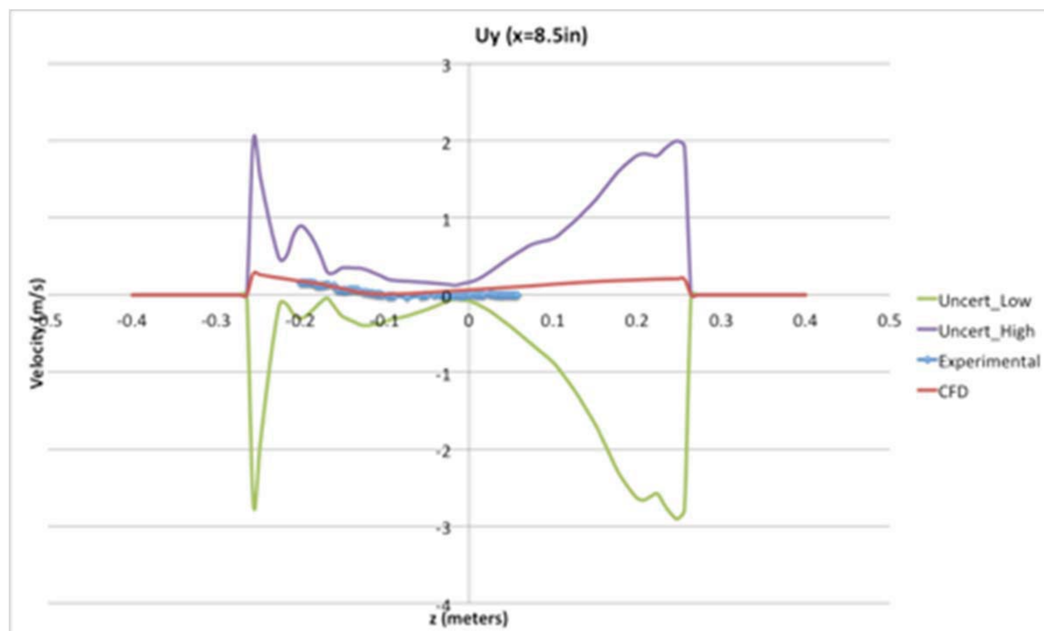


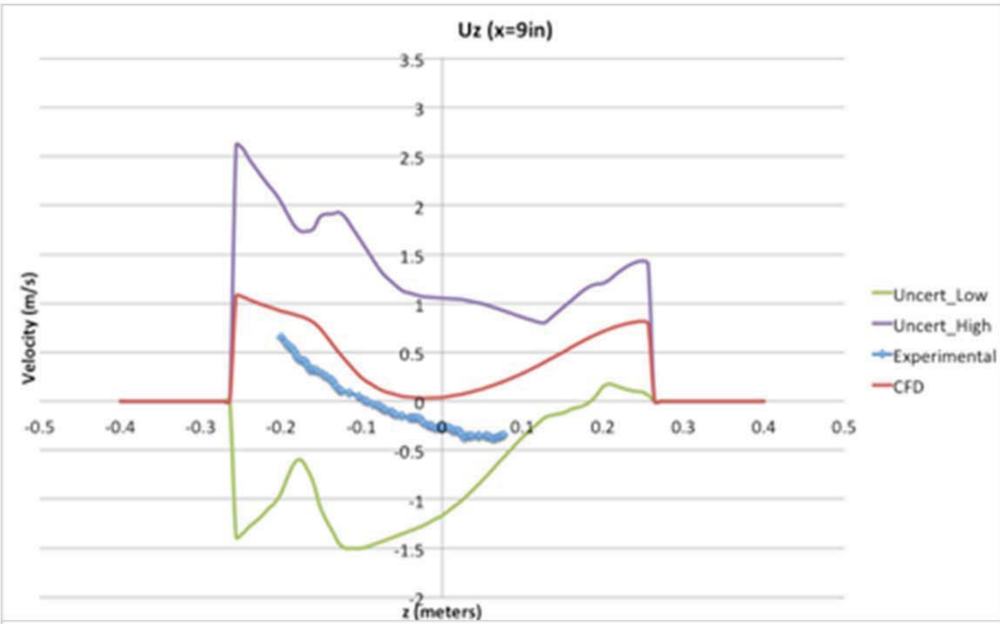


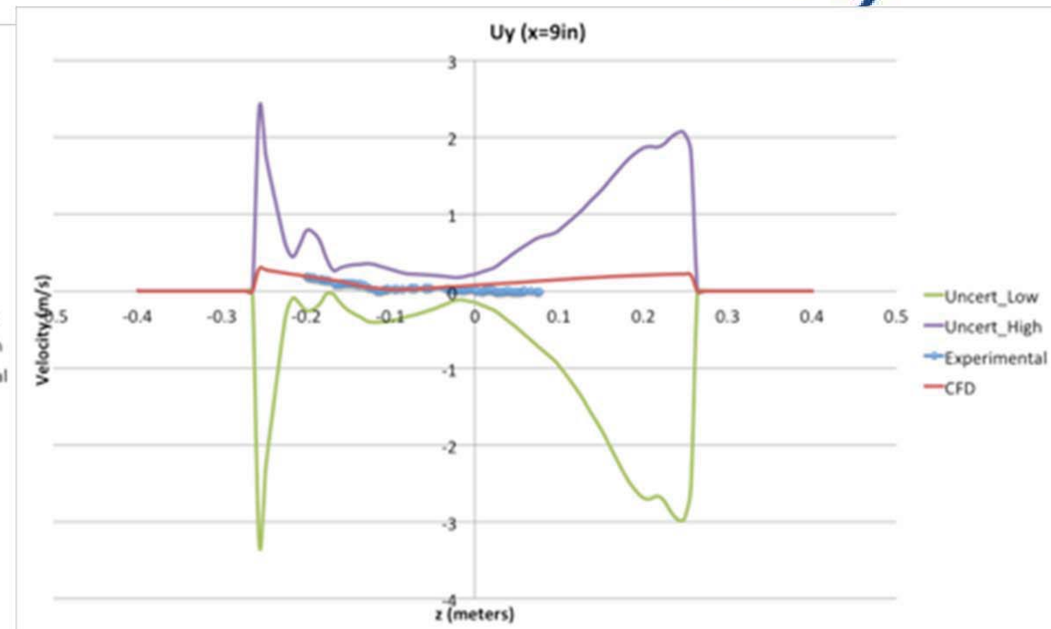


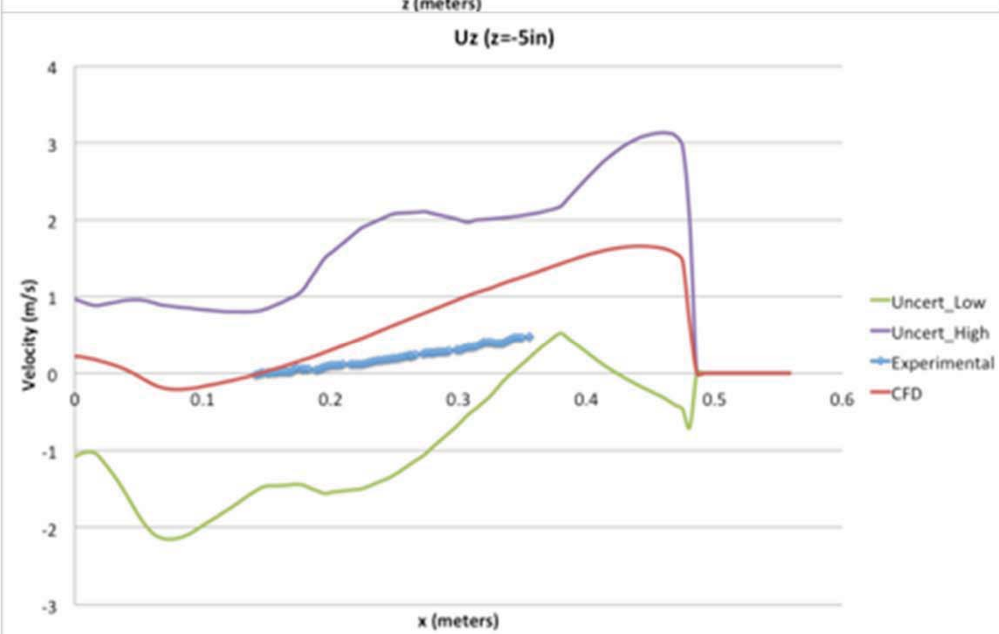


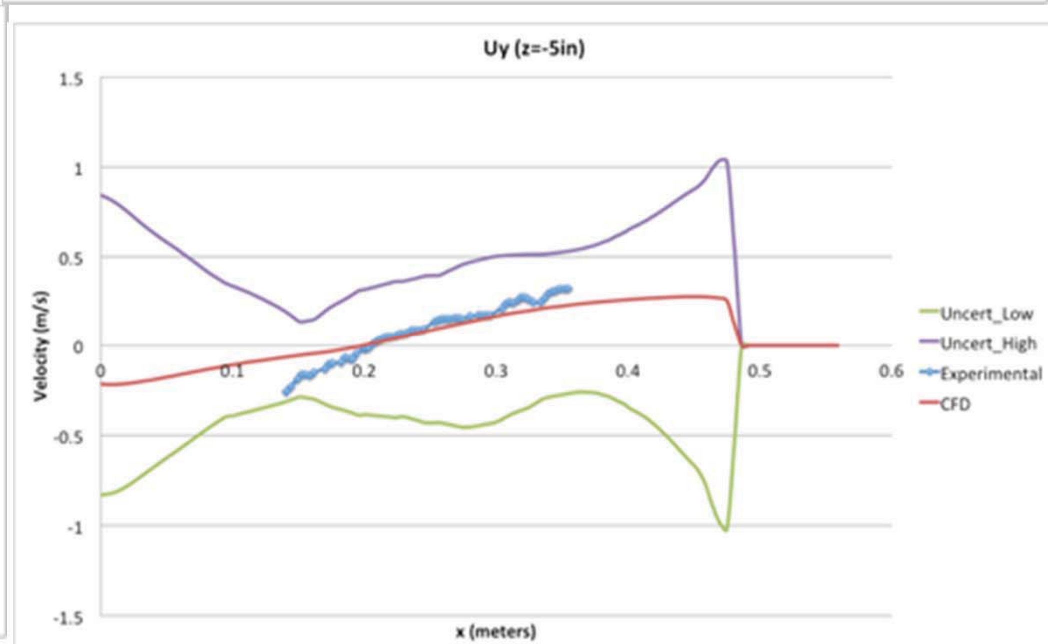
Assumes 99% Confidence

Comparison to Previous LDV Test









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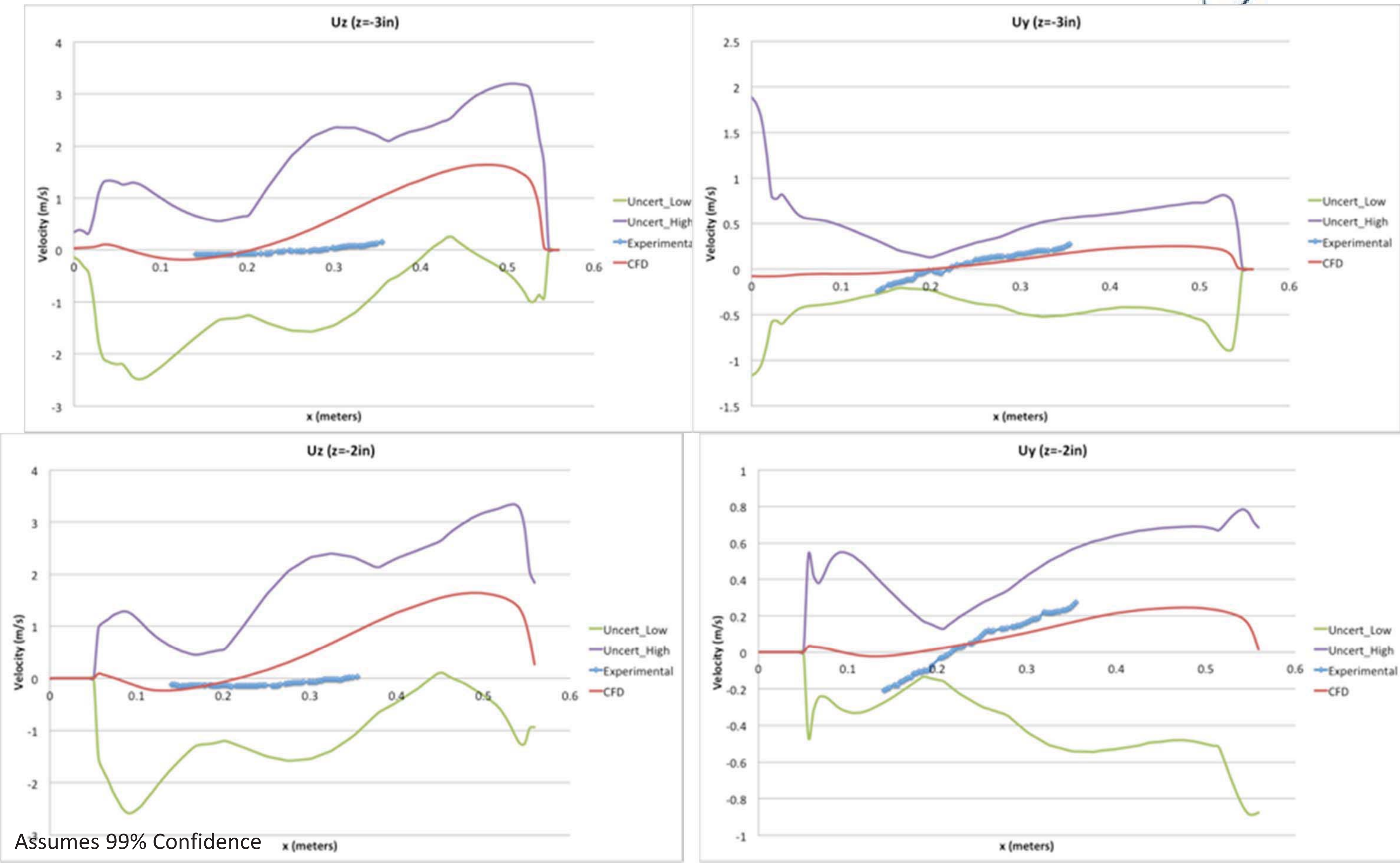

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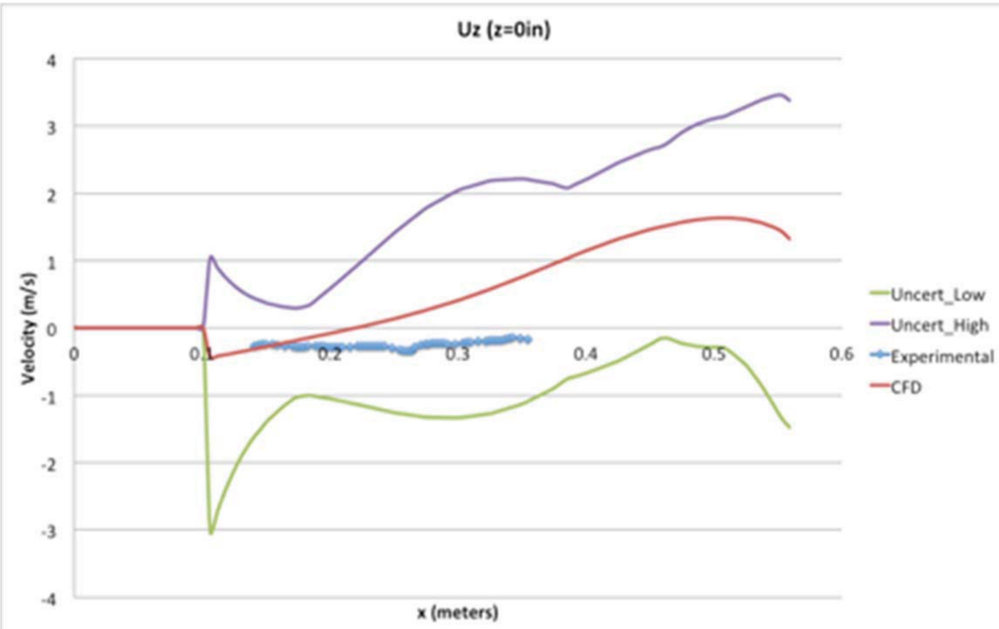

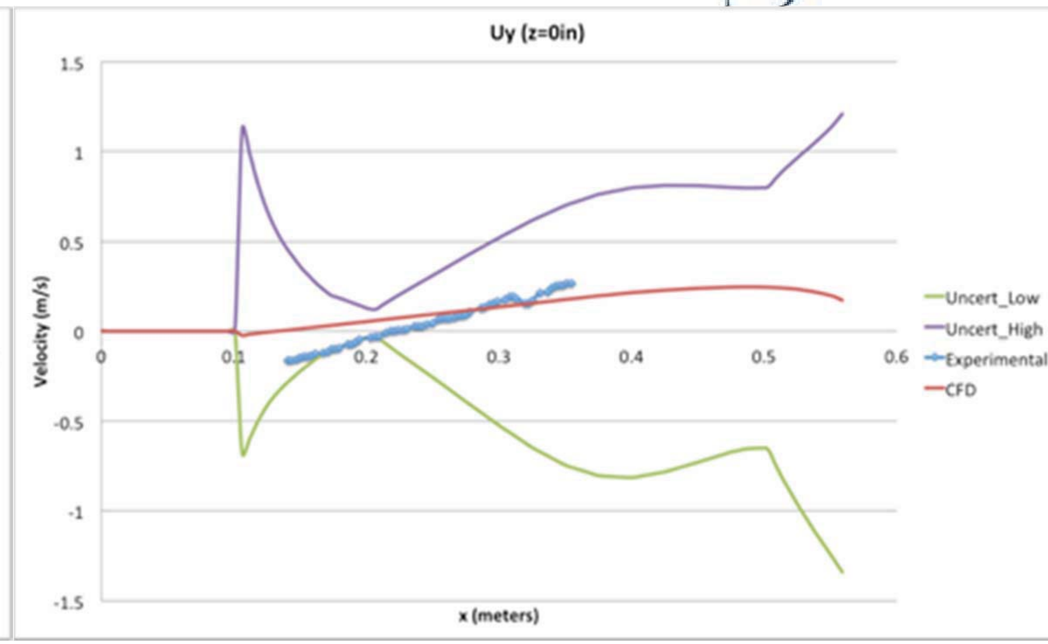

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Conclusion / Recommendation

- Proper validation with experimental data should be used to verify ECS impingement requirements
- This research proposes a CFD uncertainty methodology when experimental data is unavailable and unobtainable
  - Couples Student-T Distribution to the number of CFD models and input parameters
  - All input parameters considered had the same order of magnitude uncertainty